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Dynamic origin of stripe domains in cobalt bars

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Abstract

Based on dynamical calculations, we theoretically study the nucleation of stripe domains in single crystal Co bars. Three different stripe domain structurs at remanence are obtained in micromagnetic simulations depending on different field histories. We show that the nucleation of all three stripe domains are related to soft mode instabilities. When the field is along the long axis of the bar, the remanent stripe domain structure is shown to be generated by a standing-wave mode, that has the same spatial structure as the stripes at remanence and goes soft at a second order phase transition where the stripe domains emerge. For the two other directions of the field, we find that the symmetry of soft modes is consistent with the change in symmetry of the ground state but in these casex the phase transition is first order.

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Stripe domains are a common phenomenon observed in many different physical systems [1-4]. The existence of stripe domains in ferromagnets was first proposed by Landau and Lifshitz based on energy minimization considerations [5]. It remains unclear, however, how a system evolves into a particular stripe domain structure. Here we investigate this issue by studying a thin-film cobalt bar, which is known to develop stripe domains at remanence [6]. In micromagnetic simulations, we find that the stripe domain structure at remanence in such a system is not unique and depends on the field history. Hence energy minimization alone is not adequate to predict the exact stripe domains at remanence. To identify the dynamic origin of the stripe domains, we calculate the magnetic normal modes using a micromagnetic-based technique [7, 8]. The formation of stripe domains is found to be related to soft mode instability. In this paper we focus on the simplest case when the external field is applied along the length of the bar.

We study a single crystal *hcp* Co bar, 40 nm thick and 120 nm wide, with a uniaxial anisotropy along the width and a length of either 792 nm or 936 nm. The material parameters used in calculations are the saturation magnetization Ms=1.4 x 10^5 A/m, the exchange constant A = 3 x 10^{-11} J/m, and the uniaxial anisotropy constant K_u= 5.2 x 10^5 J/m^3; all are typical values for epitaxial cobalt films. For such a system, we obtain different stripe domains for different field histories. If a large field is applied along the long axis of the bar and reduced to zero, the long bar breaks into 13 domains and the short bar into 11 domains. If the field is applied exactly along the short axis or with a small angle, the remanent state of the short bar has five or three domains, respectively. All three stripe domains are shown in Fig. 1. The fact that the stripe domain structure at remanence is not unique implies the failure of energy minimization to predict the exact domain structure at remanence. Using simulations to find the ground state energy of a bar with an arbitrary number of domains, we find that none of the three stripe domains listed above is at the lowest energy state at zero field.

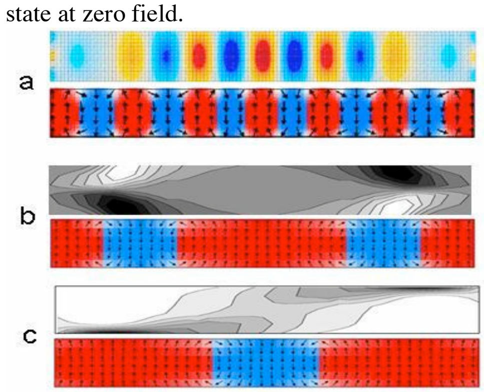

Fig. 1. (color online) Comparison of the profiles of modes that go soft at the phase transition points (upper graph of each pair) and stripe domains at remanence (lower of each pair) in three different cases: (a) external field applied along the long axis for the 936 nm bar; (b) and (c) external field applied along the short axis and at an angle to the short axis respectively for the 792 nm bar.

We now focus on the dynamic origin of stripe domains when the external field is applied along the long axis of the bar. More detailed results are published in Ref. [9]. As the field is reduced, magnetization reversal is initiated at the particle ends. Simulations on bars that differ only in length, however, show that the domain size at remanence is independent of the bar length, indicating that the final state is a bulk-like phenomenon rather than an "end effect." In this case, the bulk modes resemble standing-wave-like solutions. We calculate the dispersion relation of the standing-wave modes and find that the lowest-frequency mode is always the one with wavevector $q = 0.043\ \mathrm{nm}^{-1}$ independent of the length of the bar or the value of the field. This wavevector corresponds to a wavelength of about 146 nm, which is very close to two times of the average domain size, 72 nm, in both the long and short bar. Thus, this lowest-frequency standing-wave mode has same spatial structure as the stripe domains at remanence, as shown in Fig. 1a.

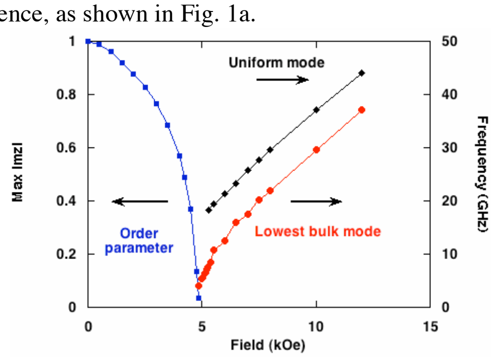

Fig. 2. (color online) Frequency as a function of applied magnetic field for the lowest frequency bulk mode and the uniform resonance mode (right axis). The left-hand side shows the evolution of the "order parameter" $|M_z|$ in the central region of the bar.

In Fig. 2 we plot the frequency of the lowest-frequency bulk mode as a function of field. For comparison, the frequency of the uniform mode is also shown. Although many other modes exist, only one bulk mode reaches zero frequency near $H = 5kOe$. Thus, in this geometry, the final state configuration is directly connected with a particular bulk mode that goes soft. Figure 2 also shows the evolution of an order parameter as a function of applied field. The squares in Fig. 2 are the maximum value of $|M_z|$ in the cells in the central portion of the bar, where z is the short axis; as such, it provides a convenient order parameter for the phase transition. Noting that the order parameter and the frequency of the lowest bulk mode extrapolate to zero at the same field and the identical symmetry between the mode profile and stripe domains, we claim that the origin of the stripe domains in this geometry is a soft magnon mode, and not the minimization of energy.

In two other cases with the field applied along the short axis and the bar breaking into either three or five domains, soft modes at the critical field are observed as well. The difference here is that the magnetization goes through a discontinuous change at a critical field and thus a first-order phase transition occurs. More interesting is that the symmetry of the soft modes are consistent with that of the change of ground states, which is clearly shown in Fig. 1b and c. Detailed results will be published elsewhere [10]. In all three cases, soft modes are responsible for the phase transitions observed in this system. An analytical model based on the dynamical matrix approach [8] provides a physical picture how the soft-mode profile determines the magnetization profile after the symmetry break in a phase transition [11]. This model applies to the formation of stripe domains discussed in this paper and other phase transitions reported in Ref. [12].

In summary, we have studied the dynamic origins of stripe domains in a Co bar. We find that soft modes are responsible for all the phase transitions observed in the system, whether first order or second order.

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References

1. C. Harrison, D. Adamson, Z. Chen, J. Sebstian, S. Sethuraman, D. Huse, R. Register, and P. Chaikin, *Science* **290** (2000), p. 1558.
2. S. Streiffer, J. Eastman, D. Fong, C. Thompson, A. Mumkholm, M. Ramana Murti, O. Auciello, G. Bai, and G. Stephenson, *Phys. Rev. Lett.* **89** (2002), p. 067601.
3. O. Portmann, A. Vaterlaus, and D. Pescia, *Nature* (London) **422** (2003), p. 701.
4. J. Smakov, D. Batista, and G. Ortiz, *Phys. Rev. Lett.* **93** (2004), p. 067201.
5. L. Landau and E. Lifshitz, *Phys. Z. Sowjetunion* **8** (1935) p. 153; *Electrodynamics of Continuous Media* (Pergamon, Oxford, 1960).
6. T. Kohda, Y. Otani, V. Novosad, K. Fukamichi, S. Yuasa, M. Nyvlt, and T. Katayama, *IEEE Trans. Magn.* **35** (1999), p. 3472.
7. M. Grimsditch, G. Leaf, H. Kaper, D. Karpeev, and R. Camley, *Phys. Rev. B* **69** (2004), p. 174428.
8. M. Grimsditch, L. Giovannini, F. Montoncello, F. Nizzoli, G. Leaf, and H. Kaper. *Phys. Rev. B* **70** (2004), p. 054409.
9. G. Leaf, H. Kaper, M. Yan, V. Novosad, P. Vavassori, R. E. Camley, and M. Grimsditch, *Phys. Rev. Lett.* **96** (2006), p. 017201.
10. R. E. Camley, G. Leaf, H. Kaper, M. Yan, and M. Grimsditch, in preparation.
11. M. Yan, G. Leaf, H. Kaper, R. E. Camley, H. Wang, and C. E. Campbell, and M. Grimsditch, Preprint ANL/MCS-P1301-1105, Mathematics and Computer Science Division, Argonne National Laboratory (2005).
12. M. Yan, H. Wang, P. A. Crowell, and C. E. Campbell, In: J. W. Clark, R. M. Panaoff, and H. Li, Editors, *Condensed Matter Theories*, **20**, Nova Science Publishers, New York (2005), p. 251.